# High-Performance Combination of Low Resolution Tactile Images Using a Bit-Based Representation

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Since the seminal work of Harmon[1] through to more recent reviews such as that of Dahiya et al.[2], the focus in the field of tactile sensing has been on creating sensors with resolutions as low as 1mm$^2$. Such specifications are justified by the simplicity of manufacturing a single resolution of skin sensor for all possible applications. Unfortunately, this approach requires not only that a robot has some means of connecting to potentially millions of sensors, but more significantly that it has some means of processing the commensurately large volume of data. The work presented here reduces the volume of data that must be processed by allowing the requirement for high resolution sensors to be relaxed and by the novel use of the bitboard data structure that has been used to represent board games for computers as well as solve complex graph problems [3].

For this work, a tactile sensor constructed from orthogonally-aligned strips of pressure-sensitive material was used to produce images of object with a resolution of 1.3cm. For each object, several images were produced differing only by sub-centimeter changes in position of the sensor or by rotations by a known angle. By aligning these so that they have a common set of axes and combining them, a composite image of higher resolution can result. This is because the re-alignment of the low resolution images causes the edges of the pixels in each image to lie in a different location. The re-aligned images will thus form new pixel edges at a finer spacing than in the original image, so forming a higher resolution composite image.

The bitboard data structure typically consists of multiple computer words, where each bit in those words represents the state of a particular spatial location. In this work each bit was used to encode the presence or absence of an object, in effect forming a monochrome image. By encoding the re-aligned tactile images in this way, the composite image could be produced simply by applying a bitwise-AND between them. This gives a high performance for processing the images, as bitwise operations are applied to all the bits in a word simultaneously. In order to achieve this in practice, the force detected by each sensor in the tactile array was processed using a threshold value to determine if a group of 169 bits (to represent a 13mm x 13mm area) should be assigned values of 0 or 1. Re-alignment of the images was undertaken by utilising bit-shifting and bit-masking operations, which also afford a high computational performance.

An alternative approach is to map the force detected by each sensor to a floating-point array of equal dimensions. Re-aligning the images and the aligned cells should give an accurate image and follows the approach of van den Heever et al. [4]. This overcomes one limitation of the bitboard approach, which is that it is just a monochrome image. An intermediate solution is to employ the bitboard approach for the initial images and their realignment, but then to count how many times each pixel in all

p. 1, 2011.

of the aligned images had a value of 1. This approach is called bitboard-counting and the results of imaging using this technique along with those for floating-point averaging and the ‘pure’ bitboard approach are shown for a typical object in Figure 1.

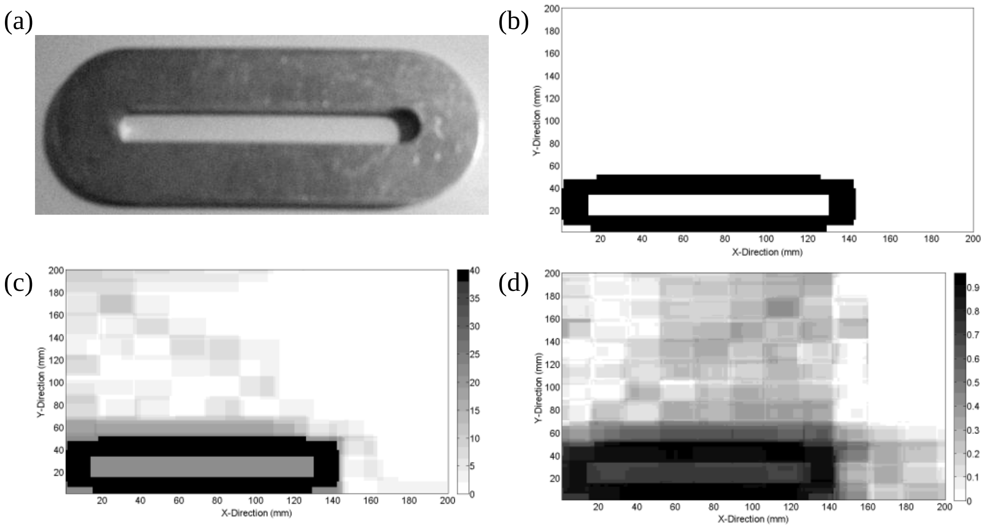


**Fig. 1.** Results of combining low resolution tactile image of object (a) using (b) pure bitboard method, (c) bitboard-counting method and (d) floating-point averaging method

The results for all three methods show an image that qualitatively represents the object being imaged and the overall dimensions correspond to those of the object to the nearest millimeter. The performance of the three methods was assessed by averaging the time for each to process the same images over 10,000 runs, as shown in Table 1.

**Table 1.** Average run times for each of the three image combination methods

| | Pure Bitboard | Bitboard-Counting | Floating-Point Averaging |
|---|---|---|---|
| Run time (sec.) | $8.54 \times 10^{-6}$ | $6.02 \times 10^{-4}$ | $1.14 \times 10^{-2}$ |

These results show improvements in performance of several orders of magnitude when using bitboard-based approaches. Combined with the ability to produce high-resolution images from low resolution sensor data, this affords significant opportunity to realise useful tactile imaging devices with a low computational cost. Further work will consider the potential for using multiple bits per cell and for exploration strategies using bitboard representations.

**Acknowledgements:** I wish to thank D. Allsopp, P. Shepherd and P. Iravani for supporting this work. This work was funded by EPSRC and OCRobotics.

## References

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